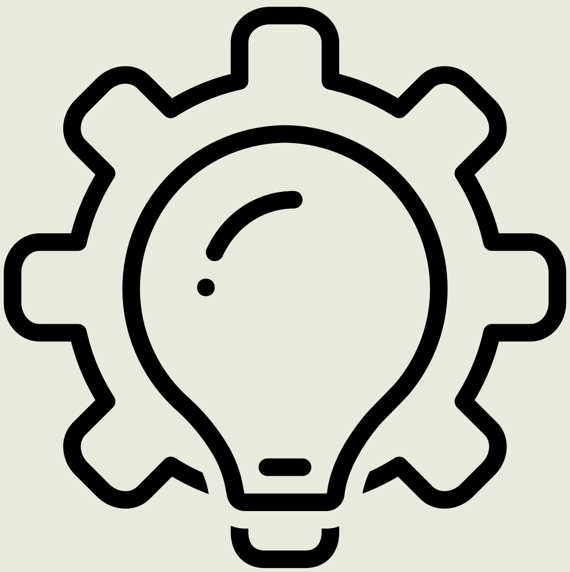
Global Innovation Needs Assessments

Methodology annex

December 22, 2021



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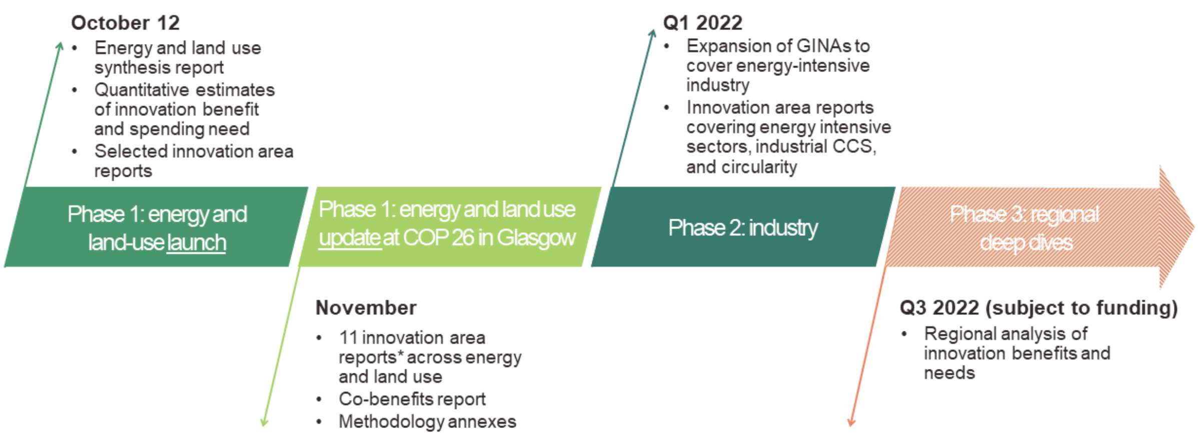
The Global Innovation Needs Assessments

The Global Innovation Needs Assessments (GINAs) is a first-of-its-kind platform for assessing the case for low-carbon innovation. The GINAs take a systemwide perspective, explicitly modeling the impact of innovations across the global economy. Uniquely, the analysis quantifies the economic benefits of low-carbon innovation and identifies the public investments—from research and development to commercialization—needed to unlock these benefits. The analysis is divided into three phases: Phase 1, global energy and land use; Phase 2, global industry; and Phase 3, regional deep dives.

The GINAs analyses neither assess all relevant technologies nor evaluates all relevant factors for policy judgments. Instead, they provide a novel evidence base to better inform policy decisions. The Phase 1 analysis examines climate mitigation technologies in energy and land use, ranging from demand response to protein diversification, to model the economic value of related innovation investment. Later phases expand this research. Like all technologies, adoption poses risks and potential downsides; some technologies in the analysis remain controversial. Which innovations to invest in is ultimately a policy judgment. This analysis provides no policy recommendations regarding investment in specific technologies.

Phases of the Global Innovation Needs Assessments



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The findings and views expressed here do not reflect the view of ClimateWorks, the Government of the United Kingdom or Mission Innovation.

Phase 1 GINA outputs

All GINAs reports and other GINAs outputs are available on the GINAs website at https://www.climateworks.org/report/ginas/.

The suite of outputs for Phase 1 of the Global Innovation Needs Assessments

1. **Energy and land use synthesis report:** slide-based summary for policymakers and executives
   Synthesis of the findings across the innovations considered in energy and land use

2. **Energy and land use and agriculture innovation reports:** in-depth quantitative analysis for industry and policy analysts

   - **Wind power** – Offshore and onshore wind turbines
   - **Low carbon hydrogen** – Electrolyzers and gas reforming with CCS
   - **Solar power** – Utility-scale and distributed PV
   - **Low carbon fuels** – 2nd generation biofuels, synthetic fuels (H_2 + CO_2)
   - **Nuclear power** – Small modular and large-scale advanced reactors
   - **System flexibility** – Battery storage, power-to-X, demand response
   - **Buildings** – Heat pumps, building fabric
   - **Power CCS** – CCS in power generation (coal, gas, and biomass)
   - **Zero-carbon road transport** – Battery electric vehicles, fuel cell electric vehicles
   - **Protein diversity** – Novel protein-rich food and feed
   - **Decarbonizing agrochemical inputs** – Innovative fertilisers and pesticides
   - **Yield enhancing technologies** – Digital agriculture and vertical farming
   - **Irrigation** – Improved irrigation methods and systems

   The selected innovation areas were selected for their potential for further innovation and the potential magnitude of the associated system benefits. Their selection here is because they could play a key role in a net zero pathway but does not imply that an optimal net zero pathway necessarily includes them. Further notes on the rationale behind their selection is provided in the methodology annex on the GINA website

3. **Co-benefits of innovation report:** qualitative analysis of the environmental and other non-economic benefits of net-zero innovation

4. **European case study:** analysis of jobs and growth benefits in Europe specifically

5. **Methodology annex:** description of the modeling approach

Introduction

The Global Innovation Needs Assessments (GINAs) provides a quantitative analysis of net-zero innovation benefits and needs. The project quantifies the payoffs from innovation in energy and land use technologies in terms of public benefits generated and gross value added (GVA) by and the jobs supported in each innovation area. The project also estimates the spending required to unlock such benefits, with the aim of raising global ambition for innovation commitments.

This annex describes the methodology underlying the key quantitative outputs of phase 1 of the GINAs project. The following topics are covered as follows:

- Section 1—Selection of technologies on which to focus
- Section 2—Estimation of the system benefits of innovation in each technology
- Section 3—Quantification of the GVA and jobs supported by increased innovation in each technology
- Section 4—Quantification of the spending required to unlock the payoffs of innovation in each technology

The methodological approach to estimate the system benefits of innovation and to quantify the GVA and jobs supported by innovation was co-developed with BEIS during the Energy Innovation Needs Assessments project, which Vivid Economics led between 2017 and 2019.

1. Selection of innovation areas

1.1 Areas of GINAs focus

The GINAs focus on innovative technologies that could play an important role in a net-zero scenario while delivering large system benefits. Using the best available evidence, the GINAs examine technologies that could be critical to achieving net-zero emissions in the global economy by reducing emissions related to energy and land use. The GINAs consider innovations that could provide the largest potential energy and land system cost reductions between today and 2050.

Three key criteria were used to select the technologies of interest:

1. **Advancement to or beyond the demonstration stage**. The GINAs focus on technologies likely to be commercialized (i.e., have reached a technology readiness level, or TRL, of at least 7) or in early stages of commercialization (i.e., at commercial readiness index, or CRI, level of 6).[1] Technologies meeting this criterion include floating offshore wind, synthetic fuels, new irrigation techniques, and next-generation electrolyzers. The analysis excludes technologies at the concept or prototype stage, such as nuclear fusion.
2. **Prominent role in credible 1.5°C scenarios**: The analysis includes technologies with wide geographic application, such as solar PV, and excludes technologies with narrow geographic application, such as tidal stream. Only technologies and innovations expected to play a critical role in 1.5°C scenarios developed by recognized research institutes were considered.[2]
3. **Substantial scope for innovation and cost reductions**: Technologies with narrow scope for further innovation and systemic cost reductions, such as hydropower, were not included in the analysis. Technologies with large potential for innovation and cost reductions, such as electrolyzers, were included. Also included were technologies, such as wind power, that have already achieved large cost reductions and that could give rise to substantial benefits due to expected widespread deployment.

Advisory panels of experts were used to validate the technologies selections. The shortlist of technologies produced using the criteria above was analyzed and validated by two advisory panels of leading innovation experts on energy and on land use, respectively. Table 1 presents the technologies shortlisted and validated for Phase 1 of GINAs.

[1] TRL ranges from 1 (in early-stage lab-based research) to 9 (ready for full-scale deployment. TRL 7 represents the prototype stage before the demonstration stage, during which technologies are tested in real-world environments. CRI ranges from 1 to 6 (a bankable asset class with known standards and performance expectations). CRI 6 typically implies commercial competitiveness with relatively low market and technology risks.

[2] Credible scenarios include those developed by IEA (2020), Energy Technology Perspectives, Breakthrough Energy (2019), Advancing the Landscape of Clean Energy Innovation (2019), Herrero et al. (2020), Innovation Can Accelerate the Transition towards a Sustainable Food System and UK Department for BEIS (2019).

Table 1. Technologies included in the GINAs Phase 1 and motivation for inclusion

Technology	Motivation for inclusion in the analysis
Wind power	Wind is a relatively mature technology but offers large system benefits because it is likely to take a large share of the global energy mix.
Solar power	Solar is a relatively mature technology but offers large system benefits because it is likely to take a large share of the global energy mix.
Low-carbon fuels	Low-carbon fuels can help decarbonize hard-to-abate sectors, such as aviation and maritime shipping.
Nuclear power	Nuclear fission provides clean dispatchable power generation that can complement variable renewable generation. R&D in nuclear fission can lead to development of nuclear technologies that are safer, cheaper, and faster to build and that produce less nuclear waste.
System flexibility	Power system flexibility is a key enabler of an energy system dominated by variable renewables. As the penetration of variable renewable sources like wind and solar increases, flexibility solutions must be developed and deployed at scale across all sectors of the energy system.
Buildings	Buildings account for almost one-third of final energy consumption globally. Electrified space heating and cooling solutions and advanced building envelope solutions can help decarbonize the sector while reducing energy demand.
Zero-carbon road transport	Battery electric vehicles are expected to be the dominant technology in light-duty transport. Fuel cells applied to heavy-duty vehicles provide potential range benefits compared to electrified freight transport.
Protein diversity	Alternative proteins could reduce reliance on animal agriculture, which is responsible for a large share of land use greenhouse gas emissions and plays a disproportionate role in water withdrawals and environmental pollution.
Yield-enhancing technologies	Gene technologies, vertical farming, and digital agriculture tools are key technologies for enhancing crop yields, which is critical for meeting growing food demand while reducing agriculture’s land and environmental footrprint.
Decarbonized agrochemical inputs	Production, distribution, and application of fertilizers and pesticides account for a significant proportion of agriculture emissions. Novel agrochemical inputs can help decarbonize the sector.
Innovative irrigation systems	Innovative irrigation systems improve irrigation efficiency, reducing water pollution. To the extent that these more efficient systems can encourage adoption of irrigation practices that increase yields, they can help decarbonize food production.

Source: Vivid Economics.

In Phase 2, the GINAs will cover heavy industry, which needs technological innovations to address hard-to-abate emissions. When this phase is completed, the GINAs will have covered key technologies across the whole energy system: power, transport, buildings, industry, agriculture, and land use.

The GINAs focal areas do not imply certainty about the future role of technologies. They reflect today’s evidence regarding the potential of low-carbon technologies to deliver net-zero emissions. However, innovation is hardly predictable. Unexpected breakthroughs and disappointments are likely.

The role of technologies in decarbonization will depend on inherently uncertain innovation processes, not to mention political choices. Technologies not covered by the GINAs might play a major role in achieving net-zero emissions. The GINAs methodology can be applied to assessment of the innovation potential and benefits of both new technologies and technologies for which expectations have substantially changed.

In the development of GINAs, some key technologies were omitted due to scope and methodological considerations. For example, low-heat geothermal and concentrated solar power are important low-carbon technologies, but their application is dependent on local conditions. Smart systems are deployed in many sectors and applications, but they are poorly captured in energy systems modeling. Electric ships and aircrafts are a promising solution for short-distance water and air transportation, but they may be not applicable to long-distance transport, which is responsible for the bulk of transport emissions. These and other technologies will likely be needed to achieve substantial emissions reductions and could be the subject of future analysis.

2. System benefits of innovation

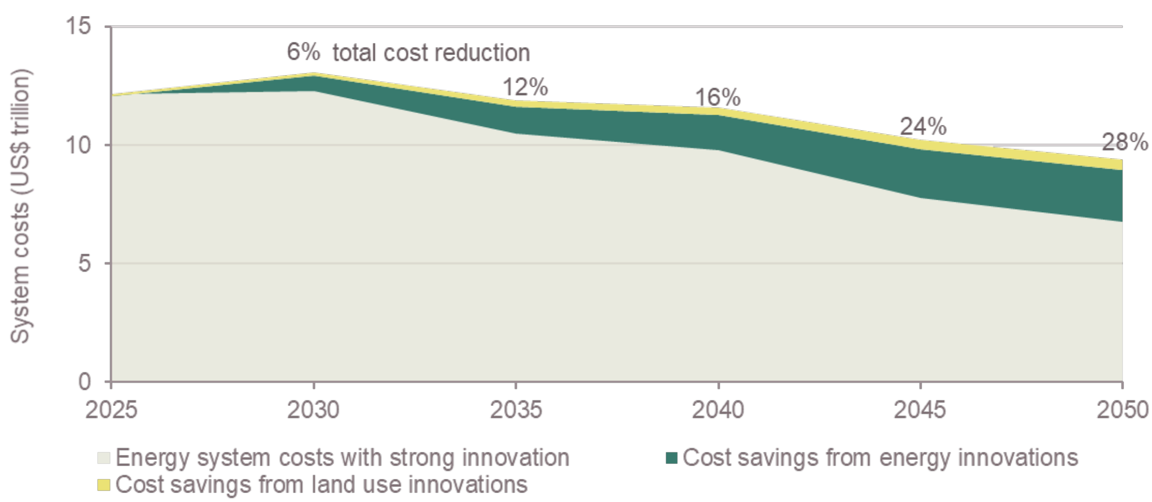
Energy system benefits

System benefits of innovation refer to the net reduction in costs across the entire energy system as a result of technology RD&D *and* commercialization. In the context of the GINAs, system benefits are calculated as the difference in the total system costs of a high-innovation scenario and those of a low-innovation scenario, whereby:

- System costs are all capital, operating, and fuel costs within the global energy system.
- Low-innovation scenario represents market-driven progress in the absence of government support.
- High-innovation scenario represents progress driven in part by government support of RD&D and deployment (i.e., commercialization).

This metric provides an aggregate estimate of how innovations in selected technologies lower the costs of 1.5°C climate ambition. System costs are calculated from least-cost optimization of all energy carriers and technologies from both the supply and demand sides, given fixed assumptions about economic growth, available resources, final demand, and other constraints (see Figure 2). All scenarios are optimized such that cumulative emissions stay within a 1.5°C carbon budget. Figure 1 shows the overall system cost reduction from innovation in energy and land use. Total system costs reach a peak in 2030 as annual deployment of renewables, new vehicles, and other technologies of interest reaches a significant level. These costs gradually decrease after 2030 as annual capacity addition starts to plateau and is outpaced by improvements in energy efficiency and cost performance.

Figure 1. System cost reductions from innovation in energy and land use.



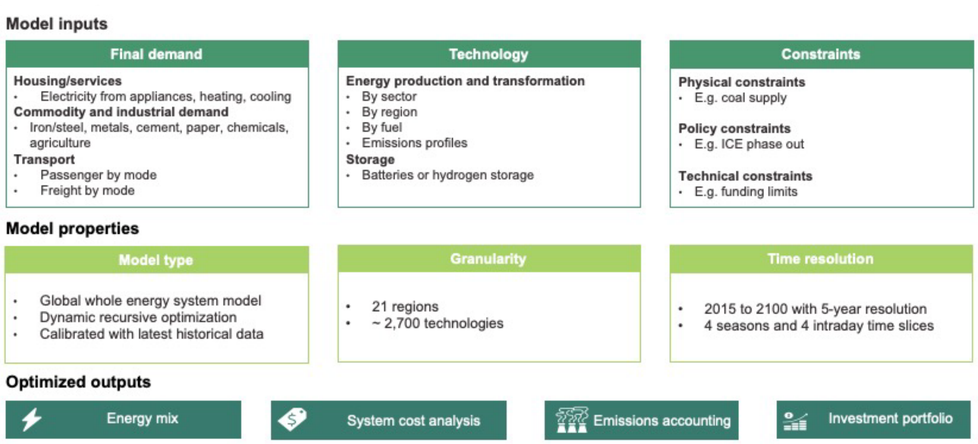
Source: Vivid Economics.

To estimate the energy system benefits of innovation, analysis of each energy technology area followed these six key steps:

1. **Compile a range of cost estimates:** For each innovation priority, a full range of technology cost estimates from 2020 to 2050 was gathered using the existing literature.
2. **Select and label cost estimates consistent with low- and high-innovation scenarios:** From the full range of technology cost estimates, the most credible ones were selected to generate two cost pathways consistent with the low- and high-innovation scenarios. The high-innovation scenario is associated with a cost pathway displaying more aggressive cost reductions than the low-innovation scenario.
3. **Insert the high-innovation cost pathway into the energy system model:** For each technology area, the cost pathway associated with the high-innovation scenario was plugged into the Vivid Energy System Model (VESM), leaving all other parameters unchanged.
4. **Run the model to obtain system costs under the high-innovation scenario**: The model performed least-cost optimization of the global energy system meeting a 1.5°C temperature target and calculated total costs to the energy system in all periods.
5. **Repeat steps (3) and (4) using the low-innovation cost pathway:** Repeating this process with the low-innovation cost estimates delivered total costs to the energy system in all periods under the low-innovation scenario.
6. **Calculate the system benefits of innovation:** The monetary value of system benefits was calculated as the difference between the total system costs in the high-innovation scenario and those in the low-innovation scenario.

The Vivid Energy System Model was used to perform least-cost optimization of the global energy system. VESM uses OSeMOSYS, the world's largest open-source energy system software model to guarantee extreme transparency and continuous validation of its structures and modules from the modeling community. It characterizes all key emitting sectors at a high level of granularity, projecting future demand in alignment with key scenarios in the literature. Figure 2 summarizes VESM's key features. Among the optimized outputs provided by the model, the key ones used in this analysis include energy mix, technology deployment, and total energy system costs over time.

Figure 2. Features of the Vivid Energy System Model (VESM).



Source: Vivid Economics.

Agricultural innovations contribute to enhancing energy system benefits through lower GHG emissions and higher carbon sequestration potential. Innovation in agriculture and land use results in lower GHG emissions from the land use system through a more efficient use of the land, creating slack in the carbon budget and reducing the cost of system-wide decarbonization. The monetary value of the climate benefits from agricultural innovations was calculated as follows:

1. **Develop plausible high- and low-innovation scenarios for each technology:** For each innovation priority, a range of improvements from 2020 to 2050 was gathered from existing literature. The improvement metric varies by innovation: market share for alternative proteins, uptake efficiency for agrochemical fertilizers, water efficiency for irrigation, and return on investment for yield-enhancing technologies. Plausible high- and low-innovation trajectories were then selected.

2. **Derive the carbon budget resulting from innovation in agriculture and land use:** The land use model MAgPIE (described in the next section) was used to calculate GHG reductions in a 1.5^{o}C scenario with high innovation in agriculture and land use relative to a 1.5^{o}C scenario with low innovation.

3. **Derive the elasticity of energy system costs with respect to the carbon budget:** The VESM energy system model was run with different carbon budgets to obtain the corresponding energy system costs. Carbon budgets and system costs were then used to calculate the change in system costs resulting from a change in the carbon budget (elasticity of cost to carbon budget).

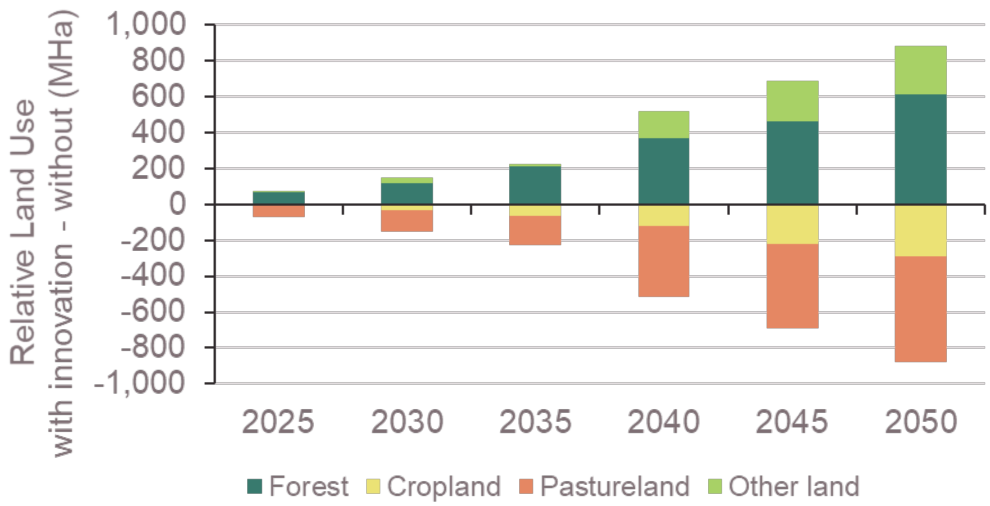
4. **Derive system benefits of innovation in agriculture and land use:** The GHG emission reductions in a scenario with high innovation were converted into a monetary value of public benefits using the elasticity of cost to carbon budget obtained from energy system modeling (as described in step 3).

Estimates represent the additional value of innovation in a world that is committed to limiting global climate change. Because the central scenario already achieves a 1.5^{o}C temperature target, the GINAs quantitative estimates are conservative, likely understating the contribution of the studied technologies to climate change mitigation, especially in the absence of other innovations or climate-specific policies. For example, diversified proteins could be associated with substantial avoided deforestation benefits even in the absence of carbon pricing and other climate policies. In the GINAs modeling, these benefits were attributed to the climate policies assumed to be in place in the central scenario, thereby understating the impact of diversified proteins. This modeling approach was taken to avoid the double-counting issues that would arise when comparing multiple innovations in the GINAs portfolio outside the context of the central scenario.

Land system benefits

Land system innovations have many benefits beyond climate change mitigation. Society relies on the land system for a wide range of services, not just carbon sequestration. Innovations that improve agricultural efficiency have benefits for many aspects of life. Figure 3 illustrates the land spared, or taken out of agricultural production and restored it to its natural state, as a result of innovations. Land sparing is incredibly important for limiting habitat and biodiversity destruction. More efficienct uses of agrochemicals and water can reduce agricultural pollution and environmental footprints. Improved efficiency lowers food costs and potentially increases human health. These benefits are explored in a GINAs report on land system co-benefits.

Figure 3. Improvements in the efficiency of agriculture with innovation.



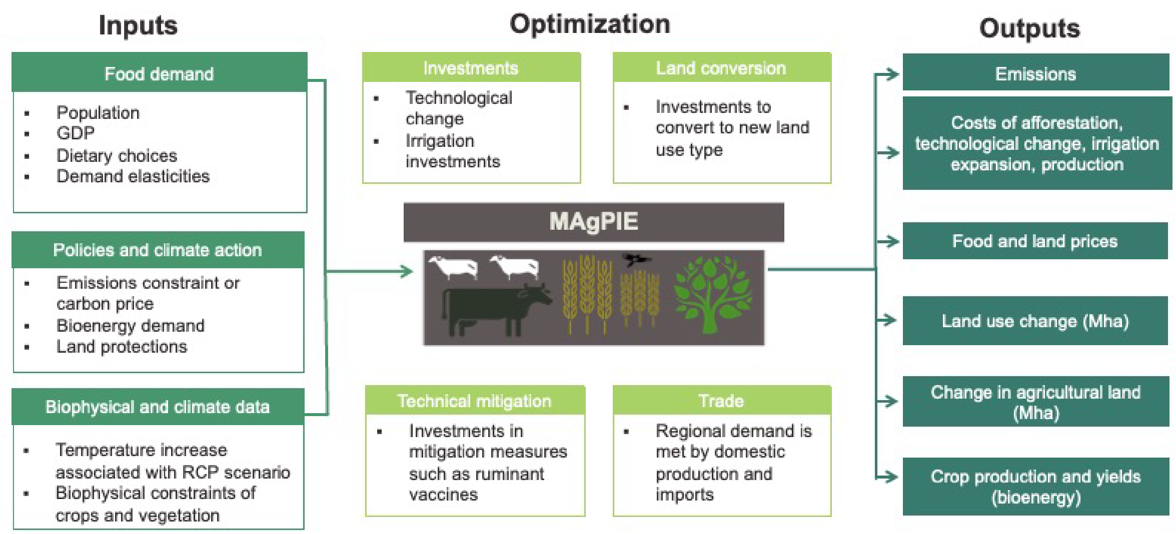
Source: Vivid Economics.

Land system benefits were estimated quantitatively where possible using MAgPIE outputs. The Model of Agricultural Production and its Impact on the Environment (MAgPIE) is a model of global land use allocation that is designed to explore land use dynamics in the context of carbon policy. Developed by the Potsdam Institute for Climate Impact Research (PIK), MAgPIE is a spatially explicit, partial equilibrium model that solves for the least-cost allocations of land uses and investment in technical change to meet future demand for food and materials of agricultural origin. The model is based on assumed population, gross domestic product (GDP), and dietary trajectories. It allows for land to be protected and set aside. It produces a land use change raster for modeled 5-year timesteps on the basis of assumptions about carbon pricing, land-related, and other policies. MAgPIE accounts for both biophysical constraints on yield, land, and water as well as for regional economic conditions. Figure 4 below summarizes the MAgPIE framework.

In addition to producing land use change estimates at each timestep, MAgPIE generates indicative cost estimates of policy instruments associated with a given action scenario. These cost estimates include land conversion costs, inputs to global food and material production, and investment in productivity enhancement and irrigation. The model outputs aggregate food and agricultural commodity prices. Thus, it indicates producers' costs and costs to consumers as well as the strength of incentives needed to effect change.

MAgPIE also estimates the GHG emissions intensity of land use. It models three GHG gases: carbon dioxide, nitrogen compounds, and methane. It accounts for CO_2 emissions from loss of terrestrial carbon stocks, including the depletion of organic matter in soils. It estimates nitrogenous emissions on the basis of nitrogen budgets for croplands, pastures, and the livestock sector, and methane emissions on the basis of livestock feed and rice cultivation areas. It records regrowth of natural vegetation as negative emissions in GHG accounts.

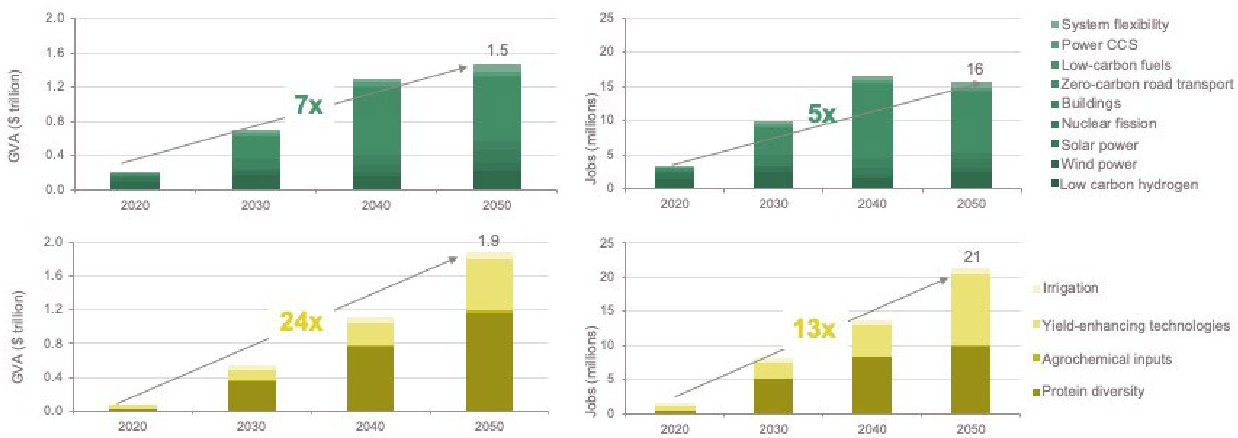
Figure 4. Features of the MAgPIE model.



3. Industry growth and employment

The GINAs quantify the industry growth and employment supported by the low-carbon technologies analyzed in a high-innovation scenario. Industry growth and employment are quantified in terms of US$ of gross value added (GVA) and number of direct full-time jobs within relevant segments of the value chain at a global level, from today to 2050. The results of this analysis are visually summarized in Figure 5. Unlike the system benefits discussed in section 2, the GVA and jobs estimates do not represent differences with respect to a low-innovation scenario. Instead, they represent the absolute size of industries and employment opportunities directly related to technology deployment.

Figure 5. GVA and jobs supported by innovation in energy and land use.



Source: Vivid Economics.
Note: In the energy sector, rapid growth in installed capacity entails substantial growth in manufacturing-related jobs in the 2030s and 2040s. This growth slows down by 2050, which see relatively more operation and maintenance jobs requiring fewer labor inputs.

Five key steps were followed to quantify GVA and jobs between today and 2050 for each technology:

1. **Define the scope of analysis:** For each technology area, a segment of the value chain was considered to quantify GVA and jobs on the basis of the potential for innovation discussed in the analysis.

2. **Fetch cost and deployment pathways from the high-innovation pathway:** Cost pathways for the high-innovation scenario were taken from the existing literature, as described in Section 2. Deployment pathways were obtained by running the energy system model using the corresponding technology cost pathways. Deployment was annualized and existing assets were considered replacements once they reached their end of life.

3. **Estimate the market size:** Within the relevant scope, market size was calculated as the product of technology deployment and unit technology cost (capex and opex). The market size was split into several broad components (e.g., construction, O&M) in the value chain using technology cost breakdowns from the most recent literature for each innovation priority.

4. **Estimate the GVA:** The market size for each component was multiplied with a proximate GVA/turnover ratio to yield an estimate of GVA:

$$GVA = Market\ size\ \times \left(\frac{GVA}{turnover}\right)$$

   The GVA/turnover ratio was estimated from ONS business statistics in proximate sectors and checked against Eurostat estimates to deliver a reasonable approximation at the global level (Office for National Statistics 2021).

5. **Estimate the jobs supported:** Multiply the GVA for each component with a proximate job/GVA ratio to yield an estimate of the number of jobs:

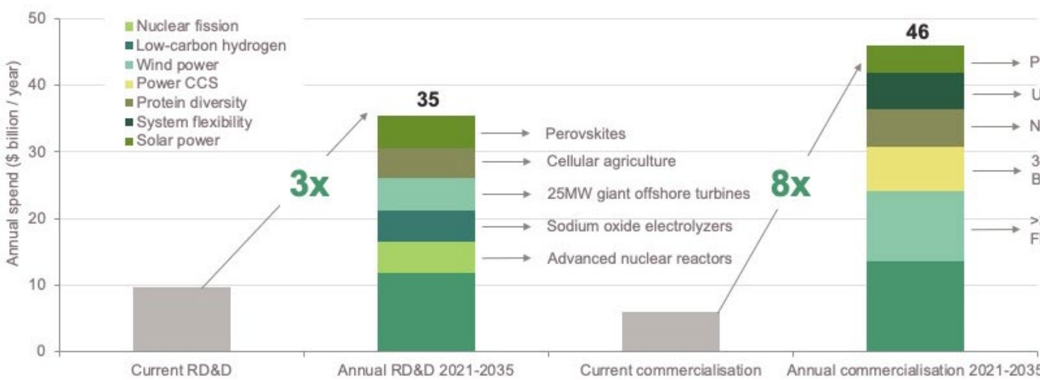
$$Jobs = GVA\ \times \left(\frac{Jobs}{GVA}\right)$$

   The ratio was estimated from ONS business statistics in proximate sectors and was scaled up to capture regional differences in productivity using World Bank data (World Bank 2021).

4. RD&D and commercialization spending

The GINAs estimated the RD&D and commercialization spending required to unlock the estimated benefits of innovation. The output of analysis of RD&D spending and commercialization spending is visually summarized in Figure 6.

Figure 6. Current and future estimates of annual RD&D and commercialization spending.



4.1 RD&D spending

Public research, development, and demonstration (RD&D) spending is aimed at demonstrating innovative technologies and has been well documented to date. This spending is aimed at helping conceptualize, build prototypes of, and demonstrate a technology in lab and field conditions. The GINAs used public RD&D spending documented by agencies such as the OECD and the IEA to estimate the public RD&D spending required to unlock the estimated system benefits of innovation.

The GINAs quantify the public RD&D spending required to unlock the estimated system benefits of innovation. For each of the energy technology areas, four key steps were followed:

1. **Establish technology cost estimates and deployment levels consistent with the high- and low-innovation scenarios:** Technology cost pathways to 2050 were obtained through steps (1) and (2) of the estimation of system benefits of innovation. Deployment levels to 2050 were obtained by running the energy system model with the corresponding technology cost pathway, as in step (4) of the estimation of system benefits of innovation.

2. **Attribute cost reductions to learning-by-doing and learning-by-research:** This step exploited the relationship among technology costs, deployment, and RD&D specified in two-factor learning curves, where

$$(1)\quad log(Cost_t) = \alpha + \beta_{LBD} log\,(Cumulative.Deployment_t) + \beta_{LBR} log\,(Cumulative.R\&D_t)$$

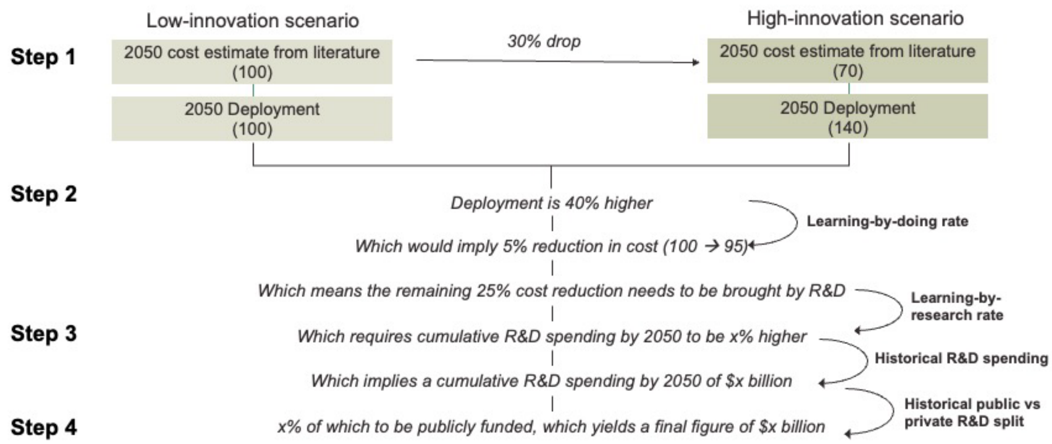
The learning-by-doing and learning-by-research rates, β_{LBD} and β_{LBR}, respectively, are selected from the available literature and are technology-specific (Rubin et al. 2015; Ouassou et al. 2021; Lafond et al. 2018; Paroussos et al. 2017; Lohwasser and Madlener 2013). Through the relationship specified in equation (1) it is possible to estimate the theoretical technology cost reduction implied by the higher deployment level in the high-innovation scenario compared with the low-innovation scenario, assuming RD&D is null. This cost reduction can be attributed to learning-by-doing. The remaining cost reduction required to match the cost pathway in the low-innovation scenario can then be attributed to learning-by-research. The percent RD&D spending increase required to deliver that remaining cost reduction can be calculated through equation (1), assuming constant underlying deployment.

3. **Estimate the innovation spending (public and private) required to yield the cost reductions achieved through learning-by-research:** The depreciated historical public RD&D spending to 2020 was obtained from the IEA Energy Technology RD&D Budget Database and was scaled up to account for China and other countries missing from the database (IEA 2021). A technology-specific assumption was made to account for the historical private RD&D spending and to scale up the RD&D budget. The depreciated historical total (public and private) RD&D spending obtained was used together with the percent RD&D increase obtained in step 2 to retrieve the cumulative public and private RD&D spending required by 2050.

4. **Estimate the share of spending that would be publicly funded:** The cumulative public and private RD&D spend were split through a technology-specific assumption about the potential future ratio between public and private RD&D to 2050. RD&D spending was calculated for the 2021–2035 period, at which point that spending was assumed to fade because new energy technologies would have reached cost competitiveness with incumbent technologies and been deployed into a mature market.[2]

[2] How long does innovation and commercialization in the energy sector take? Historical case studies of the timescale from invention to widespread commercialization in energy supply and end use technology suggest 15 to 19 years (Grosse et al. 2018).

Figure 7. Example of the method to estimate R&D spending.



Note: Numerical figures are for illustrative purposes only.

The methodology to estimate the public RD&D required for agricultural innovations differs from that used for energy innovations due to the lack of data on historical RD&D spending and on learning rates in agriculture. Spending on agricultural RD&D for climate mitigation or adaptation is poorly documented; no database allows comparisons of spending across countries and technologies. Furthermore, learning rates for most of the considered agricultural innovation areas have not yet been estimated. For these reasons, the methodology used for energy innovations could not be used in this context. Instead, the following steps were applied for each of the innovations in agriculture and land use:

1. **Estimate public benefits in terms of reduced system costs of decarbonization:** This step follows exactly the process described in section 2.2 for each agricultural innovation.

2. **Estimate the average ratio for public RD&D spending to public benefits:** This ratio is derived using (a) the average RD&D spending required for other GINAs technologies where data on historical RD&D spending is sufficient to perform bottom-up analysis and (b) their respective system benefits calculated following the approach in section 2.

3. **Apply the ratio to calculate the approximate amount of public RD&D spending required:** The public benefits quantified in step 1 were multiplied by the RD&D-to-public-benefits ratio calculated in step 2.

4.2 Commercialization spending

Public spending on commercialization is aimed at bringing technologies from demonstration to market and has not yet been documented across countries. Commercialization describes the process of incorporating new technologies into products, processes, and services and selling these technologies in the marketplace. Spending on commercialization is aimed at moving a technology from demonstration to large-scale deployment, creating markets in which producers can operate profitably. So far, historical spending on commercialization has not yet been measured or estimated systematically across countries.

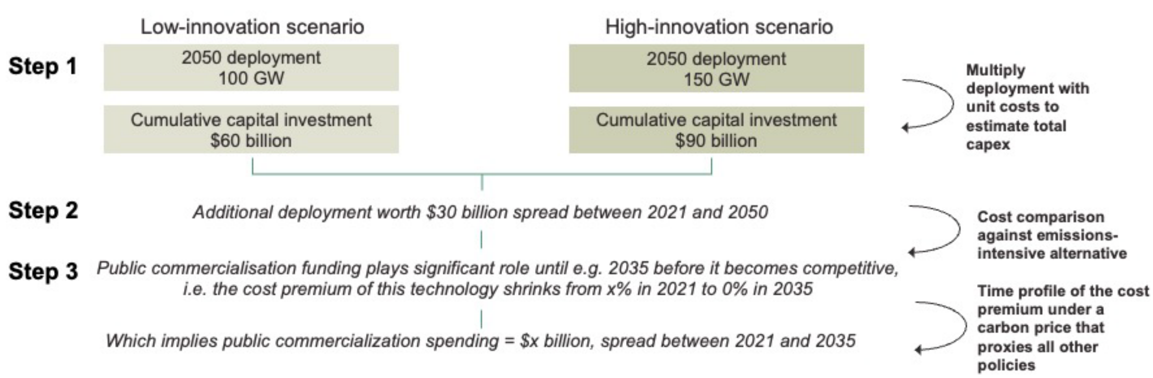
The GINAs quantify the public commercialization spending required to unlock the estimated system benefits of innovation. For each of the energy technology areas, three key steps were followed:

1. **Estimate the deployment expenditure required to build new capacity and replacements in the low- and high-innovation pathways:** The technology deployment profiles for the low- and high-innovation scenarios were obtained by running the energy system model using the corresponding technology cost pathways. Deployment profiles were multiplied with the respective technology unit costs to obtain the deployment expenditure required in each scenario.

2. **Calculate the difference between deployment expenditures across scenarios:** The difference in the deployment expenditure of the two scenarios corresponds to additional deployment thanks to a combination of commercialization spending and "pull" policies"(e.g., carbon pricing, energy efficiency standards, ICE ban).

3. **Calculate the size of public commercialization spending required to unlock additional deployment:** Public commercialization spending was assumed to fund a share of the difference in deployment expenditure across scenarios. This share corresponds to the price gap between the low-carbon technology of interest and its emissions-intensive counterpart. The price gap reduces as low-carbon technology costs drop and other pull policies take over. These policies were proxied by a carbon price that increases over time, which tends to reduce the amount of commercialization spending required as a technology becomes increasingly cost competitive. Commercialization spending is reported for the 2021–2035 period because, as noted above, it takes on average 15 to 19 years for energy technologies to reach cost competitiveness with incumbent technologies and to be deployed into a mature market (Gross et al. 2018).

Figure 8. Example of the method to estimate commercialization spending.



Note: Numerical figures are for illustrative purposes only.

The methodology to estimate the public commercialization spending required for agricultural innovations differs from that used for energy innovations due to the lack of data on future capital costs of agriculture technologies. For this reason, the methodology used for energy innovations could not be used in this context. Instead, for each of the innovations in agriculture and land use three key steps were followed:

1. **Estimate public benefits in terms of reduced system costs of decarbonization:** This step follows exactly the process described in section 2.2 for each agricultural innovation.

2. **Estimate the ratio of public commercialization spending to public benefits:** This ratio is derived using (a) the average commercialization spending required for other GINAs technologies for which CAPEX information is sufficient to perform a bottom-up estimate of commercialization spending needs and (b) their respective system benefits calculated following the approach in section 2.

3. **Apply the ratio to calculate the approximate amount of public commercialization spending required:** The public benefits quantified in step 1 were multiplied by the commercialization-to-public-benefits ratio calculated in step 2.

Conclusions

The GINAs methodology is the first of its kind for comparing the economic benefits of decarbonization with public innovation investment and without that investment. The methodology was validated by advisory panels of experts in the field. Potential improvements and extensions of the methodology include the following:

- **Simultaneous analysis of innovation in multiple technologies:** In the GINAs, innovation is modeled for each technology in isolation to capture the system benefits specifically attached to that specific technology. The interaction of multiple innovations, which is not captured in the modeling, could deliver insights about the prevailing energy mix when different innovation pathways are considered in tandem.

- **Additional forms of public finance:** The GINAs consider public support in the form of public R&D and commercialization spending. However, future analysis can consider a broader spectrum of financial instruments that differentiate forms of public finance, including instruments that can potentially mitigate risk, reduce the cost of capital, and leverage or catalyze private capital to deploy innovative technologies. Furthermore, future analysis can explicitly consider financial actors with some degree of public involvement as well as other forms of public intervention, thereby providing insights about their interaction and relative importance at different stages of technology development.

In addition to extending the scope of analysis, future analysis can update and refine assumptions. The GINAs relied on the most up-to-date data on technology cost pathways and innovation spending available. Future analysis can incorporate new information to further refine the model results.

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